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Irrigation Communities and Agricultural Water Management in Andalusia. A Special Focus on the Vega of Vélez Blanco

Summary

A freely available data set about Andalusian irrigation communities was comprehensively analyzed and combined with a local time series of precipitation and temperature data and put into historical context. Andalusia's annual precipitation lies between 150 and 1000 mm*yr^{-1}. Due to the high seasonal and inter-annual variability of precipitation, irrigation measures are a necessity to enable intensive cultivation. The largely prevailing water scarcities are one likely reason for the evolution and continuation of water cooperations practicing irrigation strategies that have probably existed since Roman times, certainly since Islamic times. This study gives an overview of water management practices in Andalusia and highlights the Vega of Vélez Blanco (NE Andalusia), as a case study.

Keywords: water balance; Spanish water management history; water scarcity; groundwater and surface water sources; agricultural water consumption

Es wurde ein freier Datensatz zu Bewässerungsgemeinschaften in Andalusien mit lokalen Klimazeitreihen vergleichend analysiert und in einen historischen Kontext gesetzt. Die durchschnittlichen Niederschlagsmengen in Andalusien variieren zwischen 150 und 1000 mm*yr^{-1}. Aufgrund der hohen saisonalen und zwischenjährlichen Schwankungen von Niederschlagsmengen ermöglichen Bewässerungsstrategien intensive Landwirtschaft. Die in weiten Gebieten herrschende Wasserknappheit ist wahrscheinlich Grund für die Entwicklung und Fortführung von Bewässerungsstrategien. Diese Strukturen haben sich vermutlich während römischer und islamischer Zeit etabliert. Der Artikel gibt einen Überblick über das Wassermanagement in Andalusien und hebt die Vega von Vélez Blanco (Nordostandalusien) als Fallbeispiel hervor.

Keywords: Wasserbalance; spanische Bewässerungsgeschichte; Wasserknappheit; Grundwasser- und Oberflächenwasser; landwirtschaftlicher Wasserbedarf

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1 Introduction

Numerous studies exist on the long history of irrigation strategies used on the Iberian Peninsula, with its different historical influences from Roman, Moorish, Iberian, and other Mediterranean cultures and schemes.[1] Irrigation is a necessity to cope with water deficits and seasonal water scarcities for the agriculture on the Iberian Peninsula, and especially for its semi-arid south. Irrigation institutions and communities that have existed in wide areas of Spain since at least medieval times are an outstanding characteristic of the area. This applies especially to Andalusia, which was the heartland of the Almoravid Dynasty during medieval times. Granada was the capital of Al-Andalus, the area of the Iberian Peninsula governed under Muslim influence the longest, lasting until the Christian reconquest. Locally, these irrigation governance systems that were installed during medieval times, function in an only slightly altered form today. Prominent examples of traditional water management systems in southeastern Spain can be found in Valencia, Murcia, and Alicante.[2] Beyond this, more than 500 irrigated areas administrated by irrigation communities currently exist in Andalusia. In total, irrigated farmland generates about 50 % of the annual agricultural income of Andalusia.[3] Many of the irrigation communities share elements of the technical infrastructure of their water management systems, like tunnels for tapping groundwater or widely distributed channels of irrigation networks. Rotation based water allocation is a common feature. In some of these communities, water is even still traditionally auctioned, as happened in Valencia, for example; meaning that additional water rights can be bought from the irrigation community by its members during regular auctions.

In this study, Andalusian irrigation communities are compared based on the aggregation and reassessment of information about their size, number of irrigation water users productivity, water balance, and local climatic conditions. On this basis, the representativeness of a concrete case study will be evaluated, namely the irrigation community of Vélez Blanco.

1 Glick 1970; Ostrom 1990; Kress 1968; Fröhling 1965; Brunhes 1902.

2 Glick 1970; Ostrom 1990.

3 Andalucía 2013.

The community of Vélez Blanco, located in northeast Andalusia, will be presented in detail as an example of the preservation of governance structures and techniques of water management.

1.1 Geographic location of Andalusia

With an area of 87 597 km^2 and a population of 8.4 million people, Andalusia is the second largest and most populated autonomous region of Spain.[4] Its landscape can be subdivided topographically into three main units: the Sierra Morena, the Guadalquivir Valley, and the Baetic System. The Sierra Morena, a low mountain range with elevations between 800–1000 m above sea level, separates Andalusia from the northern Castillian Meseta, in Spain's interior. The landscape of Andalusia is dominated in its central and western-parts by the fertile basin and alluvial plain of the Rio Guadalquivir. To the west, the Guadalquivir meets the Atlantic Ocean at the Gulf of Cádiz, where the river delta is characterized by fertile wetlands. The rough terrain of the Baetic Mountains shapes the south-east of Andalusia. With elevations above 3400 m above sea level in the area of the Sierra Nevada, this high mountain range forms a natural barrier between the Mediterranean coastline and the Andalusian hinterland (Fig. 1).

1.2 Climatic characteristics

The climate in most parts of Andalusia is Mediterranean and corresponds to a *Csa* climate, only in the southeast of Andalusia is the climate significantly drier, corresponding to a steppe climate.[5] In general, the climate mostly consists of a pronounced dry season during summer months, while most of the rainfall events occur from autumn to spring. The annual precipitation is characterized by rainfall events that most often occur during the autumn months and to a lesser extent during winter and spring.[6]

Regional differences in the climate of Andalusia are predominantly controlled by the topography and distance from the coastline. As a consequence, the strong seasonality of the Mediterranean climate is overlapped regionally by maritime influences, due to the geographical position of being adjacent to the Mediterranean Sea in the south and the east, and the Atlantic Ocean in the west. This especially applies to the spatial and temporal distribution of rainfall: In Andalusia, high regional variations of annual precipitation occur, ranging between less than 150 mm in the area of Cabo de Gata in the southeast and more than 1000 mm in the Sierra de Grazalema in the western Baetic Mountain range, whereas annual precipitation in the area of Vélez Blanco locally

4 Andalucía 2018.

5 Köppen 1936: BSk climate, C32.

6 Geiger 1970, 154–157; Rodrigo et al. 2000, 1233–1234.

Fig. 1 Topographical map of southern Spain. The autonomous region of Andalusia is highlighted. Elevation data are based on SRTM 3 data. Major divides are marked by white lines.

averages 420 mm.[7] Precipitation amounts also show a high seasonal and annual variability. In general, the occurrence of rainfall in Andalusia is controlled by two types of pressure cells, the Azores high and Atlantic lows with their related fronts.[8] Particularly during the wet season from autumn to spring, precipitation of low intensity is mainly brought to western Andalusia by low pressure cells or rain bearing clouds from the Atlantic ocean.[9] As shown by isotope analyses of Andalusian aquifers, groundwater recharge mainly comes from more intense winter precipitation originating from the Atlantic ocean.[10] The steppe-like climate of south-east Andalusia is also characterized by wet seasons in autumn and spring, but with precipitation appearing reliably only in autumn. During this time, the precipitation maxima is caused by the Balearic low from the Mediterranean Sea, a thermal depression of stationary character that emerges in September due to the thermal difference between land and water masses.[11] The winter in this

7 Pita López 2003, 15–28.
8 Rodrigo et al. 2000, 1233–1234.
9 Schütt 2004; Sumner, Homar, and Ramis 2001, 220.
10 Julian et al. 1992.
11 Lautensach 1964, 700.

	Cultivated Area		Irrigation Farming	
	[ha]	[%]	[ha]	[%]
Arable Crops	1 564 387	49.1	322 620	20.6
Olive Groves	1 358 757	42.7	359 366	26.5
Fruit Cultivation	229 515	7.2	105 649	46.0
Vineyards	26 299	0.8	2837	10.8
Other	4609	0.2	2560	46.9

Tab. 1 Main agricultural cultivations of Andalusia, Spain. The category of 'arable crops' comprises the cultivation of vegetables and cereals, Andalucía 2013.

region is usually marked by a dry phase.[12] In this area, dryness is mainly caused by the Baetic Mountains which function as a barrier to precipitation coming from the west.[13]

1.3 Aspects of agricultural production in Andalusia

Despite the fact that most areas in Andalusia struggle with water scarcity, agricultural production has a long history and is an important economic sector. More than 50 % of the region's surface is used as farmland, of which arable crops and olive groves are the main cultivation forms, while fruit farming and vineyards are – today – of minor importance. In general, agricultural cultivation can be subdivided into dry and irrigation farming, with irrigation farming practiced on approximately 25 % of the agricultural land (Tab. 1). Due to the severe dry season from June to August, irrigation farming is a frequently used tool to enable cash crop farming.

1.4 The Vega of Vélez Blanco

In the village of Vélez Blanco, eponymous for the adjoining Vega, irrigation water is still obtained by public sale at auctions that take place twice a week during summer months. Due to its special character of governance, the Vega of Vélez Blanco is described separately in this study. The remarkable – and in Andalusia, today, singular – water governance system in the Vega of Vélez Blanco was already the object of various publications.[14]

The Vega of Vélez Blanco is located in northeast Andalusia, downslope from the town of Vélez Blanco, a small town in the easternmost part of the autonomous region of Andalusia (Fig. 2). At an altitude of 1070 m above sea level, the town is embedded in the

12 Geiger 1970, 154–157.
13 Andalucía 2013.
14 Roth, Beckers, et al. 2018; Navarro Sánchez 2010; Schütt 2001; Tyrakowski 2001; Navarro López et al. 2012; Real Orden 1903.

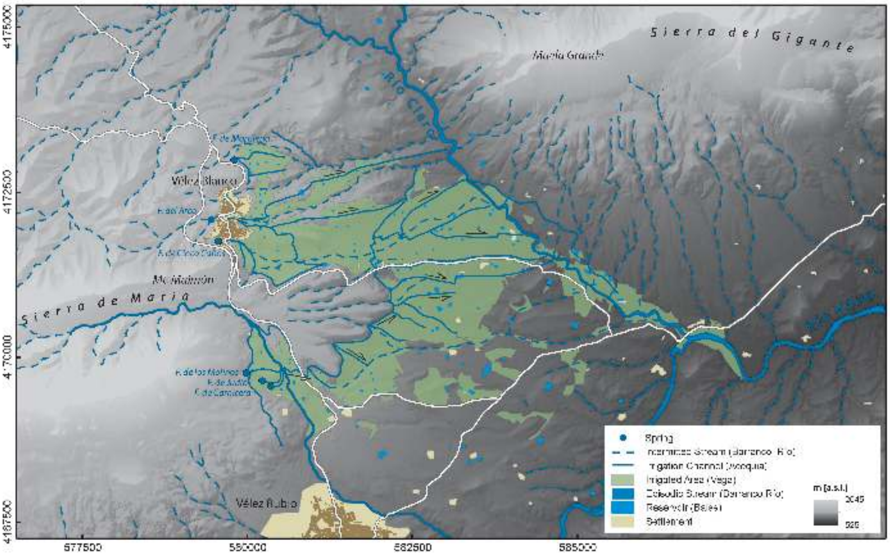

Fig. 2 Location of the Vega of Vélez Blanco. The depiction of water management infrastructure is simplified and illustrated by solid blue lines (irrigation channels) and light blue polygons (reservoirs). Elevation data are based on Lidar data (5 m resolution), Información Geográfica (CNIG) 2018.

mountainous region of the Sierra de Maria. This mountain range is primarily composed of Jurassic limestone, and is part of the southern foothills of the Baetic Mountains.[15] The springs located above the town have their source at the eastern slopes of the Mount Maimón and ensure a perennial water supply to the town and adjacent agricultural areas. The springs are fed by an extensive aquifer situated in the karstic limestone formations of the Sierra de Maria. The environs of Vélez Blanco are characterized by terraced slopes where intensive irrigation farming is practiced; this area is also known as the Vega of Vélez Blanco. Within the irrigated area, traditional cultivation such as olive and almond groves can be found, as well as vegetable gardens and orchards. In the lower parts of the Vega of Vélez Blanco, cultivation of intensive irrigated vegetables is also practiced.

15 Schütt 2001.

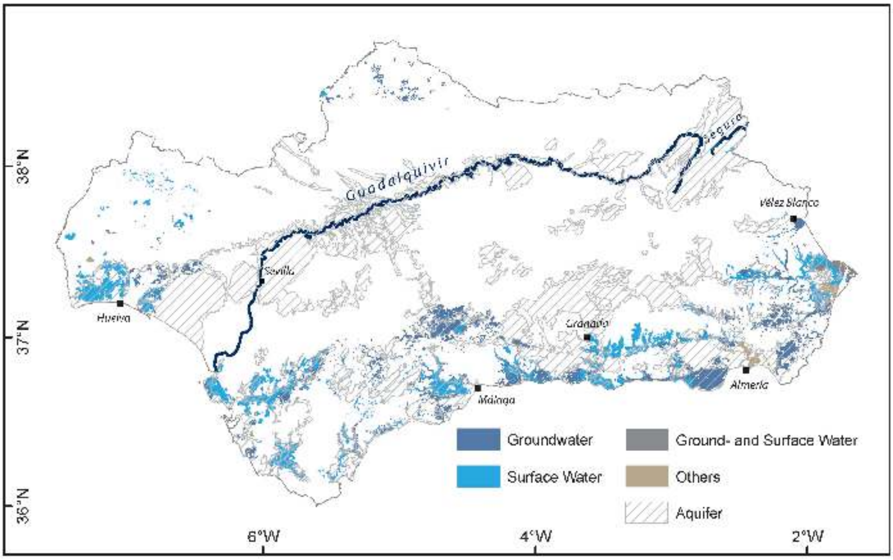

Fig. 3 Areas under irrigation in Andalusia, subdivided by the origin of the water. Locations of aquifers are indicated with grey stripes.

2 Components of Andalusia's water management history

2.1 Water utilization

Water scarcity is a serious problem in wide areas of Andalusia. The main water supply for irrigation farming originates from surface- and groundwater, with surface water supplied by streams, lakes, and reservoirs (Fig. 3).[16] Irrigation water originating from desalination of seawater and water treatment is of minor importance.[17] In addition to the physical availability of water, good technical and administrative management practices are required to achieve a sustainable distribution.

While surface water needs management techniques for its transportation, distribution, and storage, such as aqueducts, channels, and reservoirs, groundwater also needs technical facilities for its exploitation. In Spain, a traditional technique for groundwater exploitation is the so called *galería*.

This technique is similar to that of the *qanat* systems that probably originate from Persia.[18] *Galerías* are frequently used to exploit water from an upslope aquifer by tapping

16 Andalucía 2018.

17 Andalucía 2018.

18 Mays 2010.

into the waterbody via a tunnel or conduit that leads the water to a foreland outflow facility, from where it is transferred into small artificial reservoirs (*span. balsa*) where it is temporarily stored.[19] From there, the water is distributed by networks of channels to serve the fields below. Often these systems are traditionally managed by so called irrigation communities or irrigation associations (subsequently the term irrigation community will be used as an equal term for both irrigation community and irrigation association).

2.2 Historical development of the water management's legal framework and administration

In Spain, the first evidence of the implementation of water management structures dates to Roman times, though most of the present structures were established during the Muslim period (8th century BCE).[20] The Moors introduced the autonomous management of water allocation systems and improved water availability through technical advances during the medieval times.[21] Since then, a variety of transformations in administrative organization, legal ownership, and local water law have taken place, but fundamentally, the Moorish structures still provide the basis for the current Spanish water management practices and structures.[22] The first standardized guidelines for water regulation were adopted with the initial Water Act in 1866.[23] At this time, the first low degree state regulations on spatial organization and usage of water were introduced. Subsequently, a significant turn in the spatial organization of administrative water management units took place between the 1920s and 1960s, with the foundation of river basin authorities (*Confederaciónes Hidrográficas*). From here on, the drainage basins of the main streams of Spain were treated as hydrological units, defined by their natural catchment area, instead of territories limited by political borders (Fig. 4).[24]

The Water Act of 1985 has had the most significant influence on the current Spanish water management practices. Its implementation led to an almost completely revised organization of water property rights and administrative management structures. The new legislation declared all surface water, as well as renewable groundwater bodies, as public goods, except those where private ownership was adjudged by prior legislation.[25]

The multiplicity of the water management regulations implemented over time have led to the high complexity of the present administrative water management structures in Spain (Fig. 5). Large scale systems that operate on basin levels are directly supervised

19 Beckers, Berking, and Schütt 2012/2013, 148–150; Roth, Schütt, et al. 2001, 37–45.
20 Fröhling 1965, 25; Kress 1968, 131–134.
21 Boelens and Post Uiterweer 2013, 44–45.
22 Glick 1970.
23 Fornés et al. 2007, 676–677.
24 Sánchez-Martínez, Salas-Velasco, and Rodríguez-Ferrero 2012.
25 Sánchez-Martínez, Salas-Velasco, and Rodríguez-Ferrero 2012.

Fig. 4 A: Hydrological basin level administration units (Confederaciones Hidrográficas) of Spain; boundaries are defined by the major divides (black lines). The location of Vélez Blanco is indicated by the red point. The political border of the autonomous region of Andalusia is highlighted by the red line. 1 Islas Baleares, 2 Cuencas Mediterráneas de Andalucía, 3 Cuencas Atlánticas de Andalucía, 4 Cuencas Internas de Cataluña, 5 País Vasco, 6 Cantábrico, 7 Miño-Sil, 8 Galicia Costa. B: The overview map illustrates the political borders of the Spanish autonomous regions. The area of Andalusia is marked in red.

by the central government (central management), while systems of a smaller scale are usually administrated by regional and local institutions or private associations (decentralized management). It is assumed that a number of these irrigation communities were founded at least during the Muslim period. Today, only a few of these sub-systems still exist with their historical administration structures, while most of them have been transformed by external influences.

At present, a total of 586 irrigated regions exist in Andalusia, administrated by so called irrigation communities *(Comunidades de Regantes)*. Most of the irrigation communities are private and show a wide variety in size, water availability, and crops cultivated.[26] Additionally, the management of the irrigation communities varies. In principal, they can be distinguished by their characteristics in terms of the legal relationships between the land, owner, and water law. According to Butzer et al.,[27] two basic types of linkages between landownership and water law exist historically: On the one hand, there is the Syrian system, where land property is inseparable from irrigation rights, implying that each land plot is legally entitled to an amount of (irrigation) water proportional to the area. On the other hand, the Yemenite system separates the ownership of water and land, so that they can both be sold independently.

Furthermore, the irrigation communities can also be differentiated by the local organizational systems of water sharing. A frequently used method is water allocation by

26 Consejería de Agricultura 2018.

27 Butzer et al. 1985, 490.

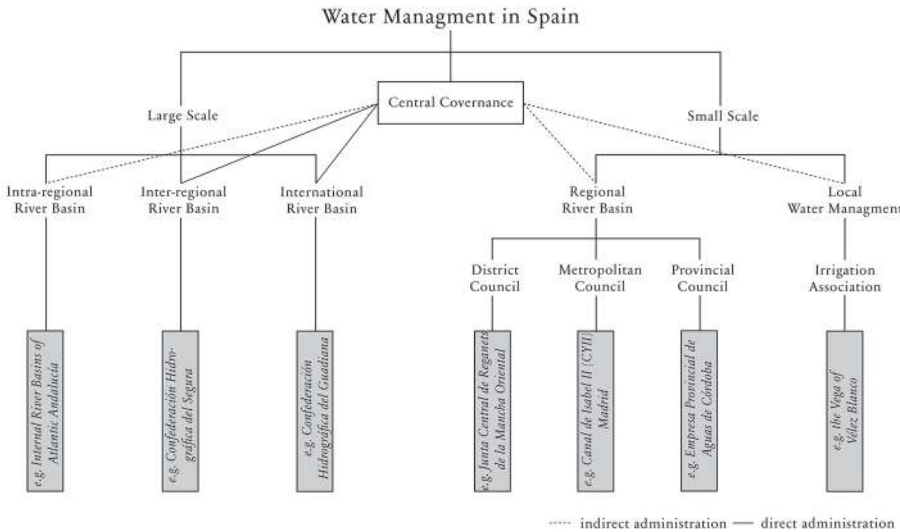

Fig. 5 Exemplary organization of the water management in Spain.

rotation, where each eligible user is entitled to receive irrigation water in a fixed turn of time units or volume.[28] Another type, is water allocation on demand, where landowners need to apply for irrigation water. The auctioning of water was a common method in the past, but is rarely found nowadays.[29] Prominent examples in south-eastern Spain, where water was auctioned in the past, are the irrigated areas of Elche, Alicante, and Lorca,[30] though most of the irrigation communities abandoned the auction-based system.

2.3 The water management system of the Vega of Vélez Blanco

With regard to its location, the Vega of Vélez Blanco (Fig. 6) represents a good example of the modern reorganization of the traditional administration. While politically the town of Vélez Blanco is part of Andalusia, its hydrological administration is the responsability of the *Confederación Hidrográfica del Segura*, that is situated in the autonomous region of Murcia. Since the local springs are traditionally managed by the local irrigation community, however, the national water management has just a marginal influence on this system.[31]

Based on knowledge about similarly structured systems in the area of south-eastern Spain, it is assumed that the local water management structures in the Vega of Vélez

28 Glick 1970.
29 Geiger 1970, 144–146.
30 Brunhes 1902; Geiger 1970, 144–146; Ostrom 1990, 69–81.
31 Navarro Sánchez 2010, 341–354.

Fig. 6 View into the Vega of Vélez Blanco (line of sight, westerly direction). The mountain Muela Grande can be seen in the background.

Blanco can at least be dated to the Muslim period.[32] Its uninterrupted irrigation history enables the investigation of an irrigation community that has been only marginally affected by large-scale restructuring plans and external institutions. Even today, the local water allocation is organized in a mixed system that consists of irrigation rotations and water auctions.[33] Within this system, each farmer with legal water rights has a fixed amount of irrigation time that is assigned to the land owned or held; landownership and irrigation rights are originally bound to each other.[34] Likewise, the irrigation community is part of the rotation system, so they also get water out of the rotations. This surplus is periodically sold during public auctions, where everybody who is connected to the channel network of the Vega of Vélez Blanco is allowed to buy a fixed amount of irrigation water.[35] Especially during dry periods in the summer months, additional irrigation water is frequently needed to gain good harvests and in some years, to avoid crop failure.

3 Materials and Archives

To determine the characteristics of the average Andalusian irrigation community, the data set *Inventario de Regadíos 2008* was used. It also includes the irrigation community of Vélez Blanco, for which several values are highlighted for comparison. The selection of numeric attributes enabled the evaluation of local hydrological and economic features within the irrigated areas.

32 Roth, Beckers, et al. 2018, 59–73.
33 Navarro Sánchez 2010, 341–344.
34 Roth, Beckers, et al. 2018, 59–73.
35 Tyrakowski 2001, 97–116.

3.1 Archives

The data set *Inventario de Regadíos 2008* is a state inventory of the irrigated areas in Andalusia. It is generated by the *Confederación Hidrográfica del Guadalquivir* as part of the national hydrological plan, and includes detailed information on a total of 979 irrigation areas supplied by fresh water that mainly originates from ground or surface waters. Additional water sources, such as desalinated seawater and treated wastewater are of minor importance. Data about local irrigation communities relevant for this study were extracted from this inventory; subsequently, only data on areas supplied by ground or surface water remained. The variables used for statistical analyses are briefly introduced in Tab. 2. They were chosen as representative characteristics for comparison.

The detailed information on cultivation and handling of the irrigated areas is based on interviews with local landowners and staff members of irrigation communities.[36]

3.2 Data preparation

The data are not normally distributed; hence all data sets were statistically edited by determining extreme values. Extreme values were calculated based on the individual interquartile range of each factor. The minimum value in Tab. 2 represents the 0.25 quartile while the maximum value marks the 0.75 quartile; extreme values that exceed the statistical boundaries defined by the interquartile range are not equal to bias within the data set. Therefore, these adjusted data were interpreted carefully. In general, all values show a high degree of dispersion. To determine measures of central tendencies, basic statistics were calculated for the processed data. Mean values extracted from the data set represent the properties of the average Andalusian irrigation community.

3.3 Water balance

Data on local water consumption and demand allow the analysis of local water balances. By plotting the parameters of consumption and demand, the individual water balance of an irrigation community is visualized. Local water consumption is calculated using information about locally cultivated goods and their respective water demand, hence water demand is estimated internally within the data set.

36 Consejería de Agricultura 2018; only values given for the *Comunidad de Regantes de las Aguas del Maimón de la Villa de Vélez Blanco* were selected as characteristic for the Vega of Vélez Blanco.

3.4 Irrigation volume

The local irrigation volumes were calculated by the quotient of water prices per area (€*ha^{-1}) and water costs per volume (€*m^{-3}). The local average volume of irrigation water was determined in cubic meters per hectare (m^3*ha^{-1}). This value allows the classification of irrigated areas in terms of its irrigation intensity. As the calculated irrigation volume is similar to the value of local water consumption, these values were applied to verify the data set.

3.5 Precipitation and temperature

The annual precipitation for each irrigation community was extracted from the global Worldclim precipitation data set with a spatial resolution of 1 km^2. The Worldclim 30 arc-seconds dataset is generated by the interpolation of climate information from a large number of weather stations with a temporal resolution for the precipitation records of at least 30 years (1960–1990).[37] This data set is known to give reliable results and is widely used in the scientific community.[38]

A dataset of daily precipitation measurements (1969–2014) from the weather station in Vélez Blanco was used to illustrate the seasonal variations of precipitation; for monthly data, the daily precipitation measurements were summed up.[39] Temperature measurements from the weather station in María, situated about 6 km west of Vélez Blanco, were used to represent the seasonal variation of the monthly mean temperature.[40] Mean values were calculated based on daily minimum and maximum temperature data.

Based on these data sets, mean values were calculated and boxplot diagrams for each month were created to outline the variation of the amount of monthly precipitation and the mean temperature during the hydrological year (Nov. 1st–Oct. 31st). Moreover, data about cycles of irrigation, blossoming, and harvesting of olives were extracted from the literature to exemplarily show the importance of precipitation variability for plant growth.

37 WorldClim – Global Climate Data 2018.

38 Hijmans et al. 2005; Avellan, Zabel, and Mauser 2012.

39 AEMET 2014.

40 AEMET 2014.

	Irrigation Communities Andalusia (n=301)				Vega of Vélez Blanco
	Mean (AIC)	Standard Deviation	Min.	Max.	
Property Size per Farmer [ha]	2.76	12.52	0.04	15.13	2.76
Irrigators per ha	2.50	3.03	0.01	28.03	0.36
Water Consumption [m^3*ha^{-1}]	3732.8	457.88	2953	4500	3000
Water Demand [m^3*ha^{-1}]	3517.4	521.63	2732	4620	2682
Water Balance [m^3*ha^{-1}]	215.4				318
Irrigation Volume [m^3*ha^{-1}]	3723.0	450.07	2953	4500	3000
Production [m^3*ha^{-1}]	3711.2	444.01	2965	4505	3217
Annual Precipitation [mm]	450.43	139.55	224	870	403

Tab. 2 Results of the statistical analysis of the Inventario de Regadíos of 2008. Since all data show high standard deviation, mean values should be handled with care. AIC: Average Irrigation Community. Data: Consejería de Agricultura 2018.

4 Results

4.1 Characteristics of Andalusian irrigation communities

In Andalusian irrigation communities, land property size per farmer averages 2.76 ha and is, in general, irrigated annually by 3700 m^3 water per hectare (m^3*ha^{-1}). The estimated water surplus of approximately 215 m^3*ha^{-1} indicates that the average irrigation community has a positive water balance. In total, annual mean productivity rates of agricultural cultivation of more than 3700 m^3*ha^{-1} are achieved by irrigation farming (Tab. 2).

The direct comparison of the Vega of Vélez Blanco with the average Andalusian irrigation community shows that the number of irrigation water users per ha in the Vega of Vélez Blanco is higher than in the average Andalusian irrigation community, while the average property size per farmer is more or less identical in both groups (Tab. 2). In contrast, the average amounts of annual water consumed and demanded, as well as those of productivity and irrigation volume, are lower in the Vega of Vélez Blanco than in the average Andalusian irrigation community.

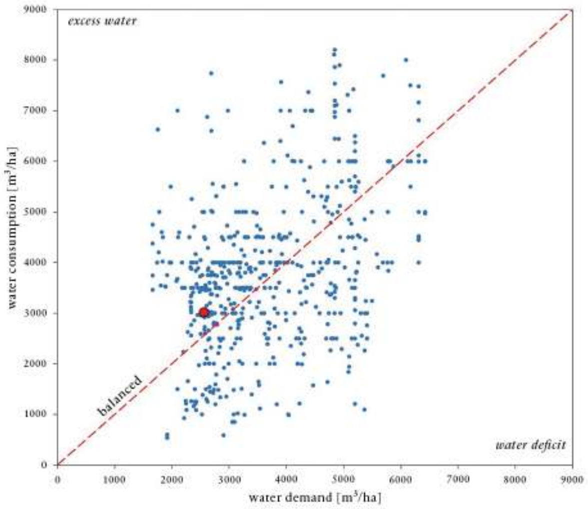

Fig. 7 Correlation of water consumption and water demand in irrigated areas managed by an irrigation community. The red line indicates the theoretically balanced water budget equilibrium. The red point marks the Vega of Vélez Blanco.

4.2 Water balance

The data show that 58.7 % of irrigated areas manages by irrigation communities in Andalusia have water excess, while 41.3 % struggle with water deficits (Fig. 7); as a consequence, nearly half of the irrigated areas in Andalusia suffer from a considerable water deficit, where the water demand for irrigation farming cannot be covered by local water resources. With an average annual water consumption of 3000 m^3*ha^{-1} and a demand of 2682 m^3*ha^{-1} the Vega of Vélez Blanco has a well-balanced water budget with a small amount of excess water.

4.3 Irrigation volume and precipitation amounts

The most intense irrigation is practiced in areas used for vegetable cropping or citrus fruit plantations; in these areas, annual irrigation capacity averages 400 $mm*ha^{-1}$ and can reach up to 800 $mm*ha^{-1}$[41]. Olive groves require less irrigation water volume, with an average amount of 290 $mm*ha^{-1}$ and maximum amounts of 780 $mm*ha^{-1}$of irrigation water.

The annual precipitation amounts in the analyzed regions range between 230–795 $mm*yr^{-1}$ (Fig. 8). Citrus fruits are planted in regions with annual precipitation amounting to up to 690 $mm*yr^{-1}$, while most plantations operate in areas with annual rainfall amounts of 300–460 $mm*yr^{-1}$. Subtropical fruits are cultivated in re-

41 Consejería de Agricultura 2018.

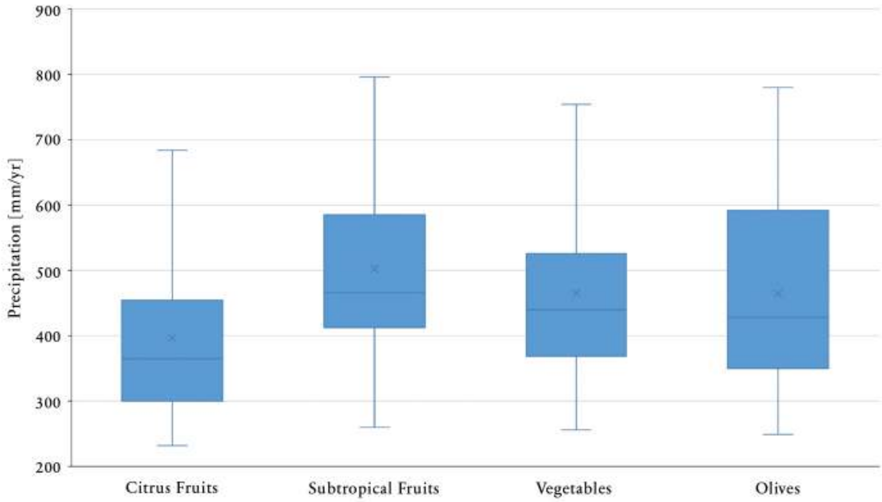

Fig. 8 Boxplot diagrams of areal precipitation ranges for irrigated areas and their respective main crops.

gions with up to 800 mm*yr^{-1}annual precipitation, where most areas receive about 410–590 mm*yr^{-1} of annual precipitation. The precipitation range of regions where vegetables and olives are cultivated correspond to those of the subtropical fruits, with olives showing the widest range of annual precipitation, spanning between 350 and 590 mm*yr^{-1}. For the data analyzed, all means were higher than the median. Summarizing, the box-plot in Fig. 8 clearly shows that the amount of annual precipitation is not the controlling factor for cropping.

More important for the selection of a crop type for a region is the relation of the respective flowering period and growing season to the annual cycle of precipitation and prevailing temperatures at a location. The demand for water for the plants usually increases during these phenological growth stages. Also, seasonal variations in temperature have a major influence on the growth of certain plants; this especially applies to plants that are vulnerable to temperatures below the freezing point.

4.4 Precipitation and temperature variability in Vélez Blanco

In Vélez Blanco, autumn is characterized by having the highest variation in monthly amounts of precipitation, with means of about 50 mm per month and extreme values of more than 240 mm (1969–2014, Fig. 9). During this time of the year, mean temperatures rapidly fall from about 17°C in September to less than 8°C in November. The months of September and November also show the lowest range of mean temperatures.

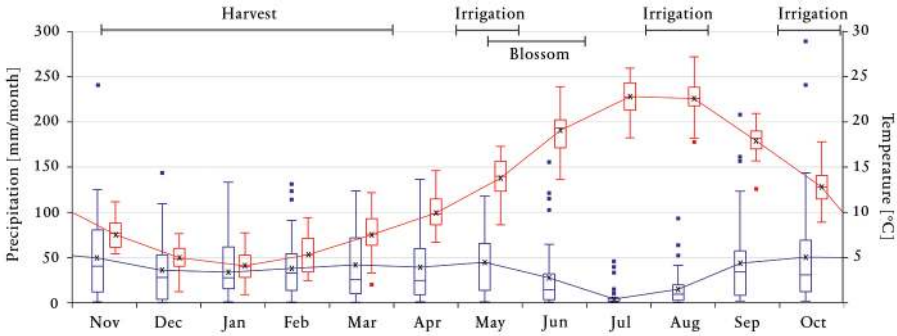

Fig. 9 Boxplot diagram of the monthly precipitation and mean temperature values (precipitation data recorded at the weather station in Vélez Blanco; temperature date recorded at the weather station in María) for a period of 45 years (1969–2014). The data is arranged in the sequence of the hydrological year (Nov. 1st–Oct. 31st). The blue boxplots and line represents the monthly mean precipitation rates, while the red boxplots and line illustrate the monthly mean temperature. Blue and red squares mark extreme values of monthly precipitation sums and mean temperature rates. The general annual cycle of irrigation, blossoming, and harvesting of olives is based on data from the FAO, FAO 2015b; AEMET 2014.

A significant low in average precipitation volume (less than 5 mm on average) marks the summer month of July, while the highest temperatures are reached in August. June and August show low precipitation amounts, averaging less than 25 mm. Winter and Spring are characterized by constant mean precipitation amounts of about 40–45 mm, where the highest variation can be observed in January and April (1969–2014). The winter months are dominated by the lowest monthly mean temperature, which show a moderate range. Highest variations in mean temperature can mainly be observed in the transition zone of the seasons.

The comparison of precipitation and temperature data from Vélez Blanco with annual general cycles for the cultivation of olives shows that the major irrigation period in August coincides with aridity and high mean temperature that marks the summer months from June to August. The low precipitation probability during this time overlaps with the flowering period of the olive trees. In contrast, the water demand of olive plantations during the start of the blossoming period in May is likely to be covered by precipitation, while additional irrigation is only required during dry springs. The same holds true for the ripening process of the olive fruits in autumn.

5 Discussion

The data set of irrigated areas in Andalusia was already used in several studies.[42] These studies share a tentative handling of the data, since much of the information provided is aggregated indirectly from interviews and remote sensing analyses. Nevertheless, this archive contains comprehensive information about irrigation communities in Andalusia that is currently openly accessible.[43]

5.1 Organization of irrigation communities in Andalusia

A literature review revealed that the degree of complexity of the administration of irrigated areas mainly depends on the number of farmers that rely on surface or groundwater.[44] Especially irrigated areas that are supplied by surface water, often need a high degree of administration, with decentralized cooperation, since these sources often supply several irrigated areas within a river's course, such as the Guadalquivir. In contrast, areas supplied by groundwater are usually small in size and, therefore, need a relatively low degree of administration. Butzer et al. defines three basic scales to classify the management of irrigated areas.[45] The smallest one is *micro-scale* irrigation, with a size of less than 1 ha. Here, an individual farmer or a few farmers use water from one small spring or a cistern. *Meso-scale* irrigation areas include one single or several cooperating irrigation communities that are supplied by water from at least one spring. On average, these systems contain up to several hundred farmers that together usually irrigate less than 100 ha. The largest unit are the *macro-scale* irrigation areas, which comprise several irrigation communities; up to several hundred cultivators can be included in these systems. The area under irrigation normally exceeds 50 km^2 and, therefore, necessitates a highly complex channel network for the water distribution, as well as a sophisticated government structure.

Based on the numeric characteristics of the Vega of Vélez Blanco and the definitions by Butzer et al. the Vega of Vélez Blanco can be classified as a meso-scale irrigation area.[46] This is also the classification for the average Andalusian irrigation community.

5.2 Vélez Blanco within the Andalusian irrigation communities

The comparison of the irrigation area of Vélez Blanco with the average Andalusian irrigation community reveals that the Vega of Vélez Blanco is a good representation of the

42 Rodríguez-Díaz et al. 2008; Solbes 2003; Salmoral et al. 2011.
43 Solbes 2003.
44 S. Garrido 2014; Butzer et al. 1985, 485–493; Hunt 1988; Lopez-Gunn 2003.
45 Butzer et al. 1985, 485–493.
46 Butzer et al. 1985, 485–493.

average Andalusian irrigation community. The only feature that distinguishes the Vega of Vélez Blanco from other Andalusian irrigation areas is the tradition of auctioning irrigation water during the summer months. The prevailing mixed system of irrigation rotations and water auctions has lasted centuries in approximately the same administrative form that is still in place today, while other irrigation communities of Andalusia abandoned this type of organization.[47] A well-known example is the *Huerta de Lorca*, located in western Murcia, where water auctions where abolished in 1961.[48]

Since water is an important resource for the development of local economic and social structures, transformations in water availability or its quality can influence these developments.[49] As shown by Boelens and Uiterweer,[50] a change in political or economic conditions, for example, the governmental reorganization of administrative structures, can trigger transformations of organizational water management systems.[51] In the most recent water management history of Spain, large scale water allocation programs led to a completely revised organization of local and regional water management systems. These restructuring plans have deconstructed self-governance systems in many regions that had previously worked in a self-organized way for centuries.[52] Substantial imbalances in regional water supply were the initial reason for this reorganization. According to the analyzed inventory, more than half of the irrigated areas of Andalusia show a positive water balance, whereas water demand exceeds the natural availability in 41.3 % of the areas.[53]

5.3 Water balance

Water consumption and demand in the Vega of Vélez Blanco is approximately balanced. Thus, on average, the given water resources are sufficient to supply the cultivated crops. This general statement does not include seasonality and inter-annual variations. An extended dry season, as well as a drought or a sequence of years with below average annual rainfall, can lead to an increased water demand and, thus, to a shift towards an unbalanced water regime.

The main crop cultivated in Andalusia are olive groves. In total, they cover more than 40 % of the irrigated land of the autonomous region.[54] Olives require water, especially during their growth periods in May, August, and October in order to obtain good harvests.[55] To produce a harvest, the minimum amount of water required during

47 Roth, Beckers, et al. 2018.
48 Geiger 1970, 144–146.
49 Custodio et al. 2016, 314.
50 Boelens and Post Uiterweer 2013.
51 Boelens and Post Uiterweer 2013, 53–57.
52 Boelens and Post Uiterweer 2013, 53–57.
53 Fröhling 1965, 17–23; Geiger 1970, 144–153; Saurí and Moral 2001.
54 Andalucía 2013.
55 Galán et al. 2008, 100–104.

this time totals 200 mm, while the highest crop yields are achieved with 600–800 mm of water during that time; as in most cases, these water amounts are not provided by precipitation, irrigation is required.[56] Most importantly, irrigation is required about two to three week prior to the flowering period of the olive trees.[57] Olive groves in irrigated areas of Andalusia that are administrated by an irrigation community receive 230–795 mm of annual precipitation, which should be adequate to receive low to sufficient yields without irrigation. However, due to the seasonal and inter-annual variations in precipitation, irrigation is frequently required to improve harvests or secure crops. Especially during the main growing seasons in the summer months, irrigation is often used to bridge the dry season to improve the crop yields.

Vegetables and cereal fields cover nearly half of the cultivated surface area of Andalusia.[58] Based on data found in the literature, vegetable crops such as tomatoes, peppers, cabbage, and onions need on average 350–900 mm of annual precipitation to achieve adequate crop yields.[59] Within the irrigated areas of Andalusia, these agricultural products are usually cultivated in regions where annual precipitation ranges from 250–760 mm. Here, likewise, annual sums of precipitation provide no reliable information about the natural water supply of the cultivated crops during the growth season. The cultivation of most vegetables in Andalusia needs intensive irrigation.

Agricultural production in the Vega of Vélez Blanco is dominated by olive and almond groves. A small area of intensively irrigated vegetables can also be found in the lower part of the Vega of Vélez Blanco. These vegetable gardens are mainly for private consumption.

As literature sources and the case study from Vélez Blanco show, for most of the cultivated goods represented in this study, the main periods of growth coincide with the dryness and high temperatures of the summer months. Additionally, cold winters with temperatures below freezing, as well as a hot summers with extended dry periods can result in crop failures. An example is provided with the olive tree; long lasting periods of frost with temperatures of -10°C and below lead to poor harvests and even to crop failure.[60] Furthermore, various plants cultivated in Andalusia are very sensitive to fluctuations in temperature. As a consequence, especially in the driest parts of Andalusia, irrigation is necessary to ensure good harvests for agricultural goods such as olives.

One of the challenges concerning irrigation farming is the cultivators' profit orientation. Frequently, cash crop farming is practiced in areas where climate conditions barely suite the natural needs of the cultivated crops during their growth periods and, hence,

56 FAO 2015b.
57 Caliandro and Boari 1992, 24–27.
58 Andalucía 2013.
59 FAO 2015e; FAO 2015d; FAO 2015a; FAO 2015c.
60 Steduto et al. 2012, 303–308.

high yields can only be achieved by intensive irrigation. Especially in areas where irrigation is supplied by groundwater, the higher water demand for irrigation often results in an increased exploitation of groundwater.[61] In fact, the extraction of groundwater with deep wells has increased dramatically since the 1950s, leading to an uncontrolled overexploitation of groundwater bodies,[62] triggered by private farmers, as well as by large companies. Consequently, human-induced intensification of the already existing natural water scarcity is increasingly becoming a serious problem in large areas.[63]

6 Conclusions

The comprehensive analysis of the state inventory *Inventario de Regadíos*, in combination with a literature review, enables new insights into Andalusian irrigation communities and reveals some of the challenges they face.

From this we conclude, that:

(i) An average Andalusian irrigation community is characterized by a property size of roughly 3 ha per farmer, which is fed by about 3700 m3*ha-1 of irrigation water.

(ii) 41 % of the irrigation communities suffer water deficits concerning their respective crops, while nearly 60 % of the irrigation communities have an excess of water in regards to their irrigation demands for cultivation.

(iii) The high seasonal and spatial variability of precipitation in Andalusia means that, in many regions, it is necessary to irrigate crops to safeguard harvests and avoid crop loss.

(iv) The outstanding feature that distinguishes the Vega of Vélez Blanco from other irrigated areas is the tradition of auctioning irrigation water.

61 Custodio et al. 2016; Salmoral et al. 2011.

62 Geiger 1970, 148.

63 A. Garrido et al. 2009, 57–58.

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